FEMTOSCOPIC CORRELATIONS OF NONIDENTICAL PARTICLES*

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The formalism and assumptions behind the correlation femtoscopy are briefly reviewed. The femtoscopy techniques, with the emphasis on correlations of nonidentical particles, are discussed.

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1. Introduction

The momentum correlations of two or more particles at small relative momenta in their center-of-mass (c.m.) system are widely used to study space-time characteristics of the production processes on a level of fm $= 10^{-15}$ m, so serving as a correlation femtoscopy tool (see reviews [1–7]). In fact, the femtoscopic correlations due to the Coulomb final state interaction (FSI) between the emitted electron or positron and the residual nucleus in beta-decay are known for more than 70 years (see [8] for a discussion of the similarity and difference of femtoscopic correlations in beta-decay and multiparticle production). The femtoscopic correlations due to the quantum statistics (QS) of produced identical particles were observed almost 50 years ago as an enhanced production of pairs of identical pions with small opening angles (GGLP effect). The basics of the modern correlation femtoscopy were settled by Kopylov and Podgoretsky in early seventieth of the last century. Besides the space-time characteristics of particle production, the femtoscopic correlations yield also a valuable information on low-energy strong interaction between specific particles which can hardly be achieved by other means [6].

In the following, I will concentrate on femtoscopy techniques applied to the analysis of unlike particle correlations in relativistic heavy ion collisions. One can inspect recent reviews [4-7] for a number of other important topics.

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2. Formalism

The ideal two-particle correlation function $\mathcal{R}(p_1, p_2)$ is defined as a ratio of the measured two-particle distribution to the reference one which would be observed in the absence of the effects of QS and FSI. In practice, the reference distribution is usually constructed by mixing the particles from different events with similar topology, normalizing the correlation function to unity at sufficiently large relative velocities. This procedure is well justified for high-energy collisions involving nuclei since they are characterized by sufficiently large multiplicity of produced particles and, in the absence of QS and FSI, the particle correlations at small relative velocities are negligibly influenced by kinematic constraints and production dynamics.

Usually, it is assumed that the correlation of two particles emitted with a small relative velocity is influenced by the effects of their mutual QS and FSI only and that the momentum dependence of the one-particle emission probabilities is inessential when varying the particle four-momenta p_1 and p_2 by the amount characteristic for the correlation due to QS and FSI (*smoothness assumption*). As for the former assumption, besides the rare events with a large phase-space density fluctuations, it may not be justified also in low energy heavy ion reactions when the particles are produced in a strong Coulomb field of residual nuclei; to deal with this field a quantum adiabatic (factorization) approach can be used [9]. The latter assumption, requiring the components of the mean space-time distance between particle emitters much larger than those of the space-time extent of the emitters, is well justified for heavy ion collisions.

The correlation function is then given by a square of the properly symmetrized Bethe–Salpeter amplitude in the continuous spectrum of the two-particle states, $\Psi^{S(+)}_{p_1p_2}(x_1, x_2)$, averaged over the four-coordinates $x_i = \{t_i, \boldsymbol{r}_i\}$ of the emitters and over the total spin S of the two-particle system [10, 11]. On the assumption of the quasi-free propagation of the low-mass two-particle system, one can separate the free c.m. system motion in the unimportant phase factor. As a result, this amplitude practically reduces to the one, $\psi^{S(+)}_{\widetilde{q}}(\Delta x)$, depending only on the relative four-coordinate $\Delta x \equiv x_1 - x_2 = \{t, \boldsymbol{r}\}$ and the generalized relative momentum $\widetilde{q} = q - P(qP)/P^2$, where $P = p_1 + p_2$, $q = p_1 - p_2$ and $qP = {m_1}^2 - {m_2}^2$; in the two-particle c.m. system, $\boldsymbol{P} = 0$, $\tilde{q} = \{0, 2\boldsymbol{k}^*\}$ and $\Delta x = \{t^*, \boldsymbol{r}^*\}$.

At equal emission times of the two particles in their c.m. system ($t^* \equiv t^*_1 - t^*_2 = 0$), the reduced non-symmetrized Bethe–Salpeter amplitude coincides with a stationary solution $\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*)$ of the scattering problem having at large distances r^* the asymptotic form of a superposition of the plane and outgoing spherical waves (the minus sign of the vector $\boldsymbol{k}^*$ corresponds to the reverse in time direction of the emission process).

Note that, to simplify the calculations, the reduced Bethe–Salpeter amplitude is usually substituted by the equal-time amplitude $\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*)$. For non-interacting particles, the reduced non-symmetrized Bethe–Salpeter amplitude coincides with the plane wave $e^{i\tilde{q}x/2} \equiv e^{-i\boldsymbol{k}^*\boldsymbol{r}^*}$ which is independent of the relative time in the two-particle c.m. system and so, coincides with the corresponding equal-time amplitude. On the contrary, the amplitude of two interacting particles contains an explicit dependence on t^* — the interaction effect vanishes at $|t^*| \to \infty$. However, it can be shown [10] that the effect of non-equal times can be neglected on condition $|t^*| \ll m(t^*)r^{*2}$, where $m(t^* > 0) = m_2$ and $m(t^* < 0) = m_1$. This condition is usually satisfied for heavy particles like kaons or nucleons. But even for pions, the $t^* = 0$ approximation merely leads to a slight overestimation (typically less than a few percent) of the strong FSI effect and, it does not influence the leading zero-distance ($r^* \ll |a|$) effect of the Coulomb FSI [10, 11].

In the *equal time* approximation, the correlation function

$$\mathcal{R}(p_1, p_2) \doteq \sum_S \widetilde{\rho}_S \left\langle \left| \psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) \right|^2 \right\rangle_S ; \tag{1}$$

for identical particles, the amplitude in Eq. (1) enters in a symmetrized form:

$$\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) \to \left[\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) + (-1)^S \psi^{S(+)}_{\boldsymbol{k}^*}(\boldsymbol{r}^*) \right] / \sqrt{2} \,. \tag{2}$$

The averaging in Eq. (1) is done over the four-coordinates x_1, x_2 of the emitters according to the two-particle emission function $G_S(x_1, p_1; x_2, p_2)$ at a given total spin S of the two particles, $\widetilde{\rho}_S$ is the corresponding population probability, $\sum_S \widetilde{\rho}_S = 1$. For unpolarized particles with spins s_1 and s_2 the probability $\widetilde{\rho}_S = (2S+1)/[(2s_1+1)(2s_2+1)]$. Generally, the correlation function is sensitive to particle polarization. For example, if two spin-1/2 particles are initially emitted with polarizations $\boldsymbol{\mathcal{P}}_1$ and $\boldsymbol{\mathcal{P}}_2$ then [10] $\widetilde{\rho}_0 = (1 - \boldsymbol{\mathcal{P}}_1 \cdot \boldsymbol{\mathcal{P}}_2)/4$, $\widetilde{\rho}_1 = (3 + \boldsymbol{\mathcal{P}}_1 \cdot \boldsymbol{\mathcal{P}}_2)/4$.

3. Femtoscopy techniques

3.1. Identical particles

For identical pions or kaons, the effect of the strong FSI is usually small and the effect of the Coulomb FSI can be in first approximation simply corrected for (see [12] and references therein). The corrected correlation effect is then determined by the QS symmetrization only, *i.e.* the Bethe–Salpeter amplitudes have to be substituted by properly symmetrized combinations of the plane waves. As a result, $\mathcal{R}(p_1, p_2) = 1 + \langle \cos(q\Delta x) \rangle$.

Assuming, for example, that for a (generally momentum dependent) fraction λ of the pairs the particles are emitted by independent one-particle emitters that are at rest and differ only by the four-coordinates of their centers characterized by the Gaussian space-time dispersions r_0^2, τ_0^2, while for the remaining fraction $(1-\lambda)$, related to very long-lived emitters (η, K_s^0, Λ, ...), the relative distances r^* between the emission points in the pair c.m. system are extremely large, the correlation function

$$\mathcal{R}(p_1,p_2) = 1 + \lambda \exp\left(-{r_0}^2\boldsymbol{q}^2 - {\tau_0}^2 q_0^2\right) . \tag{3}$$

We see that a characteristic feature of the correlation function of identical spin-0 particles is the presence of an interference maximum at small $|\boldsymbol{q}|$, changing to a horizontal plateau at sufficiently large $|\boldsymbol{q}|$, large compared with the inverse characteristic space-time distance between the particle emission points.

The on-shell constraint $q_0P_0 = \boldsymbol{qP}$ makes the q-dependence of the correlation function essentially three-dimensional (particularly, in pair c.m. system, $q\Delta x = -2\boldsymbol{k}^*\boldsymbol{r}^*$) and thus makes impossible the unique Fourier reconstruction of the space-time characteristics of the emission process. However, within realistic models, the directional and velocity dependence of the correlation function can be used to determine both the duration of the emission and the form of the emission region [1], as well as — to reveal the details of the production dynamics (such as collective flows; see, *e.g.*, reviews [4–7]). For this, the correlation functions can be analyzed in terms of the out (x), side (y) and longitudinal (z) components of the relative momentum vector $\boldsymbol{q} = \{q_x, q_y, q_z\}$ [13, 14]; the out and side denote the transverse components of the vector $\boldsymbol{q}$, the out direction is parallel to the transverse component of the pair three-momentum. The corresponding correlation widths are usually parameterized in terms of the Gaussian correlation (femtoscopy or interferometry) radii r_i, *e.g.*, for spin-0 bosons

$$\mathcal{R}(p_1,p_2) = 1 + \lambda \exp\left(-r_x^2q_x^2 - r_y^2q_y^2 - r_z^2q_z^2 - 2r_{xz}^2q_xq_z\right) , \tag{4}$$

and the radii dependence on pair rapidity and transverse momentum is studied. The correlation strength parameter λ can differ from unity due to the contribution of very long-lived emitters, particle misidentification and coherence effects. Equation (4) assumes azimuthal symmetry of the production process. Generally, *e.g.*, in case of the correlation analysis with respect to the reaction plane, all three cross terms q_iq_j contribute.

It is well known that particle correlations at high energies usually measure only a small part of the space-time emission volume, being only slightly sensitive to its increase related to the fast longitudinal motion of particle emitters. In fact, due to limited emitter decay momenta of few hundred MeV/c, the correlated particles with nearby velocities are emitted by almost comoving emitters and so — at nearby space-time points. The dynamical examples are resonances, colour strings or hydrodynamic expansion. To substantially eliminate the effect of the longitudinal motion, the correlations can be analyzed in terms of the invariant variable $Q = 2k^* \equiv (-\widetilde{q}^2)^{1/2}$ and the components of the three-momentum difference in the pair c.m. system ($\boldsymbol{q}^* \equiv \boldsymbol{Q} = 2\boldsymbol{k}^*$) or in the longitudinally comoving system (LCMS) [15]. In LCMS, each pair is emitted transverse to the reaction axis so that the generalized relative three-momentum $\widetilde{\boldsymbol{q}}$ coincides with $\boldsymbol{q}^*$, except for the *out*-component $\widetilde{q}_x = \gamma_t q_x^*$, where γ_t is the LCMS Lorentz factor of the pair.

3.2. Nonidentical particles

The FSI effect allows one to access the space-time characteristics of particle production also with the help of correlations of non-identical particles. One should be however careful when analyzing these correlations in terms of simple models like those assuming the Gaussian space-time parametrization of the source. While the QS and strong FSI effects are influenced by large r^*-separations mainly through the correlation strength parameter λ, the shape of the Coulomb FSI is sensitive to the distances as large as the pair Bohr radius (hundreds of fm for the pairs containing pions).

This problem can be at least partially overcome with the help of imaging techniques [16] or transport simulations. The former require the a priori knowledge of the correlation strength (purity) parameter and yield the $\boldsymbol{r}^*$-distribution inverting the measured correlation function using the integral Eq. (1) with the kernel given by the wave function squared. The latter account for the dynamical evolution of the emission process and provide the phase space information required to calculate the QS and FSI effects on the correlation function.

Thus, the transport RQMD v.2.3 code was used in a preliminary analysis of the NA49 $\pi^+\pi^-$, π^+p and π^-p correlation data from central Pb + Pb 158 A GeV collisions [6]. The model correlation functions $\mathcal{R}_{\rm RQMD}(Q;s_r)$ have been calculated weighting the simulated pairs by squares of the corresponding wave functions. The scale parameter s_r, multiplying the simulated space-time coordinates of the emitters, was introduced in the model correlation function to account for a possible mismatch of the r^*-distribution. For this, a set of correlation functions $\mathcal{R}_{\rm RQMD}(Q;s_r^i)$ was calculated at three chosen values s_r^i of the scale parameter and the quadratic interpolation was used to calculate $\mathcal{R}_{\rm RQMD}(Q;s_r)$ for arbitrary value of s_r (see [11] for some more details). The NA49 correlation functions were then fitted by

$$\mathcal{R}(Q) = N\left[\lambda\mathcal{R}_{\rm RQMD}(Q;s_r) + (1-\lambda)\right] \tag{5}$$

with two additional parameters, the normalization N and the correlation strength (purity) λ. The results of the example fit of $\pi^+\pi^-$ correlation function shown in Fig. 1 demonstrate a good theoretical description of the extremely precise correlation data (even the errors of the lowest-Q points are on a per mill level), as well as the sensitivity to the scale parameter and strong FSI. The fitted values of the λ-parameter are in reasonable agreement with the expected contamination of $\sim 15\%$ from strange particle decays and particle misidentification. The fitted values of the scale parameter show that the RQMD transport model overestimates the r^*-separations of the pion and proton emitters by 10–20% thus indicating an underestimation of the collective flow in this model.

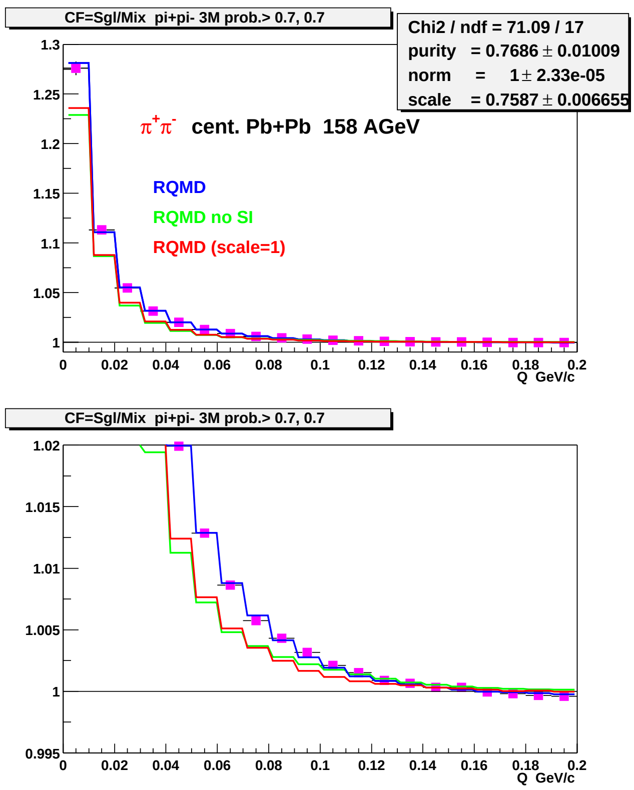

Fig. 1. The preliminary result of the fit [6] of $\pi^+\pi^-$ correlation function from 3M events of central Pb + Pb 158 A GeV collisions collected by NA49 Collaboration at SPS CERN. The lower panel shows the same correlation function with enlarged vertical scale. The histograms RQMD, RQMD (scale = 1) and RQMD no SI correspond (in decreasing order at $Q < 70$ MeV$/c$) to the RQMD prediction fitted according to (5), RQMD with the fixed scale parameter $s_r = 1$ and RQMD with the switched off strong FSI, respectively.

The shape of the correlation function is less influenced by r^*-tails in the case of two-particle systems with the absent Coulomb FSI, *e.g.* in the case of $p\Lambda$ system. In fact, the fits of $p\Lambda$ correlations in heavy ion collisions using the Gaussian parametrization of the r^*-separation yield the Gaussian correlation radii of 3–4 fm [6] in agreement with the radii obtained from pp correlations in the same experiments.

3.3. Correlation asymmetries

The correlation function of non-identical particles, compared with the identical ones, contains a principally new piece of information on the relative space-time asymmetries in particle emission [17]. Since this information enters in the two-particle FSI amplitude through the terms odd in $\boldsymbol{k}^*\boldsymbol{r}^* \equiv \boldsymbol{p}_1^*(\boldsymbol{r}_1^* - \boldsymbol{r}_2^*)$, it can be accessed studying the correlation functions $\mathcal{R}_{+i}$ and $\mathcal{R}_{-i}$ with positive and negative projection k_i^* on a given direction $\hat{\imath}$ or, — the ratio $\mathcal{R}_{+i}/\mathcal{R}_{-i}$. For example, $\hat{\imath}$ can be the direction of the pair velocity or, any of the out (x), side (y), longitudinal (z) directions. In LCMS, we have $r_i^* = r_i$, except for $r_x^* \equiv \Delta x^* = \gamma_t(\Delta x - v_t\Delta t)$, where γ_t and v_t are the pair LCMS Lorentz factor and velocity. One may see that the asymmetry in the out (x) direction depends on both space and time asymmetries $\langle\Delta x\rangle$ and $\langle\Delta t\rangle$. In case of a dominant Coulomb FSI, the intercept of the correlation function ratio is directly related with the asymmetry $\langle r_i^*\rangle$ scaled by the pair Bohr radius a:

$$\mathcal{R}_{+i}/\mathcal{R}_{-i} \approx 1 + 2\langle r_i^*\rangle/a\,. \tag{6}$$

The difference between the correlation functions $\mathcal{R}_+$ and $\mathcal{R}_-$ yields a robust estimate of the asymmetry $\langle r_i^*\rangle$ though, its statistical error is not minimized. The lowest possible statistical error is achieved by giving a weight $|\hat{k}_i^*| = |\cos\psi_i|$ to each pair contributing to $\mathcal{R}_+$ or $\mathcal{R}_-$. This corresponds to least squares fitting or moment method (yielding $2\langle r_i^*\rangle/a = \langle\hat{k}_i^*\rangle/3$) and decreases the statistical error of the $\mathcal{R}_+$ *versus* $\mathcal{R}_-$ method by a factor of $(4/3)^{1/2}$ (corresponding to a 33% gain in statistics) [18].

Besides the asymmetry information in the first order moments $\langle\hat{k}_i^*\rangle$, a useful information about the anisotropy of the $\boldsymbol{r}^*$-separation of particle emitters can be extracted also from the higher order moments. Thus, a systematic expansion of the correlation function in terms of Cartesian or spherical harmonics and a study of the corresponding $(2l + 1)$ real Q-dependent angular-moment coefficients for each order $l = 0, 1, \ldots$ has been suggested [19].

It appears that the out correlation asymmetries between pions, kaons and protons observed in heavy ion collisions at CERN and BNL are in agreement with practically charge independent meson production and, assuming

$m_1 < m_2$, with a negative $\langle \Delta x \rangle = \langle x_1 - x_2 \rangle$ and/or positive $c\langle \Delta t \rangle = c\langle t_1 - t_2 \rangle$ on the level of several fm [6, 20]. In fact they are in quantitative agreement with the RQMD transport model as well as with the hydro-motivated blast wave parametrization, both predicting the dominance of the spatial part of the asymmetries generated by large transverse flows.

In the thermal approach, the mean thermal velocity is smaller for heavier particle and thus washes out the positive spatial shift due to the flow to a lesser extent. As a result, $\langle x_\pi \rangle < \langle x_K \rangle < \langle x_p \rangle$. The observation of the correlation asymmetries in agreement with the mass hierarchy of the shifts in the out direction may thus be considered as one of the most direct signals of a universal transversal collective flow [6].

4. Correlation measurement of strong interaction

One can also use the correlation measurements to improve knowledge of the strong interaction for various two-particle systems. In the collisions involving sufficiently heavy nuclei, the effective radius r_0 of the emission region can be considered much larger than the range of the strong interaction potential. The FSI contribution is then independent of the actual potential form [21]. At small $Q = 2k^*$ and a given total spin S, it is determined by the s-wave scattering amplitude $f^S(k^*)$ [10]. In case of $|f^S| > r_0$, this contribution is of the order of $|f^S/r_0|^2$ and dominates over the effect of QS. In the opposite case, the sensitivity of the correlation function to the scattering amplitude is determined by the linear term f^S/r_0.

The possibility of the correlation measurement of the scattering amplitudes has been demonstrated [6] in a preliminary analysis of the NA49 $\pi^+\pi^-$ correlation data within the RQMD transport model. For this, besides the r^*-scale s_r, the strong interaction scale s_f has been introduced in the RQMD correlation function $\mathcal{R}(Q; s_r, s_f)$, rescaling the original s-wave $\pi^+\pi^-$ scattering amplitude: $f(k^*) \to s_f f(k^*)$; it approximately corresponds to the rescaling of the original scattering length $f_0 = 0.23$ fm. The fitted parameter $s_f = 0.6 \pm 0.1$ appears to be significantly lower than unity (see [11] for the discussion of possible systematic errors). To a similar but somewhat weaker rescaling (~ 0.8) point also the recent experimental data on pionium lifetime, K_{l4} and $K^\pm \to \pi^\pm\pi^0\pi^0$ decays as well as the two-loop calculation in the chiral perturbation theory with a standard value of the quark condensate [11]. The correlation technique was also used to estimate the singlet $\Lambda\Lambda$ and $p\bar{\Lambda}$ s-wave scattering length [6, 22].

5. Conclusions

A wealth of data on femtoscopic momentum correlations of various particle species ($\pi^\pm, K^{\pm,0}, p^\pm, \Lambda, \Xi$) is available and will rapidly increase in future experiments. Despite the integral femtoscopic correlations of nonidentical particles are usually essentially weaker than those of identical particles (with the exception of some two-baryon systems), they already provided a valuable complementary space-time information on the production characteristics including non-Gaussian tails, sequence of particle emission and collective flows. Thus the most direct evidence for a strong transverse flow in heavy ion collisions at SPS and RHIC follows from the observed mass hierarchy of unlike particle correlation asymmetries (simply related to the lower thermal velocities of heavier particles), in addition to the evidence obtained from spectra and like pion correlations. Since the femtoscopic correlations are concentrated in the region of nearly equal particle three-velocities, the corresponding tracks of nonidentical charged particles (contrary to the identical ones) are well separated in the detector magnetic field and so there is no problem with the two-track resolution. Though, in the case of very different masses a large detector acceptance is required. Also, a good particle identification and reasonable knowledge of particle fractions from long-lived emitters is required to diminish the systematics in the fit of purity parameter. The momentum correlations between specific particles also yield a valuable information on the strong interaction hardly accessible by other means, thus opening a good perspective for such an analysis of future high statistics correlation data from RHIC and LHC.

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